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Set-Based Evaluation Tool (SET): A Software Analysis Tool to Support Set-Based Decision Methods

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Abstract

This paper describes a software analysis application, the Set-Based Design Evaluation Tool (SET), which supports an innovative accelerated acquisition methodology for rapidly informing prototyping investments across the Navy and Marine Corps. The tactics and technology exploration and experimentation (TnTE2) method is fostering innovation and is used to quickly respond to high-priority urgent or emerging operational needs. This methodology brings together operational and technical teams of warfighters and engineers, leveraging aspects of a systems engineering methodology called Set-Based Design (SBD) to rapidly assess emerging technologies and engineering innovations against a specific capability-based framework. The basis of this practice is rooted in the SBD systems engineering construct to enable data-based decision-making. The SET software automates the analysis by coding the configuration evaluation portion of SBD into a user-friendly application to significantly increase the speed of analysis, reduce the chance of data input error, and standardize the reporting. Specifically, SET provides a streamlined and systematic way to

- Create a Capability Concept Wheel
- Quickly process extremely large data sets (trillions)
- Integrate and process/filter data
- Produce concise visuals of data relationships and solution alternatives
- Provide reports of analysis results

Its demonstrated benefits include enabling *users* to understand and rapidly assess interdependencies between requirements, components, and variables of large and complex data sets; providing a means for *decision-makers* to explore the tradespace and perform cost versus capability trade-offs; and giving *leaders* an automated tool to maintain and manage evolving requirements.

Introduction

In today's world, new technological breakthroughs seem to occur daily. SpaceX successfully launches the heaviest rocket in history into space, and then precisely lands its two booster rockets on their designated landing pads. Robots from Boston Dynamics effortlessly scramble over rough terrain with perfect balance, and easily open closed doors and walk through. Medical technologists around the world print human hearts, kidneys, and livers in the race to produce the first viable 3-D printed organ that can be implanted in the bodies of people on long organ donor lists. Each of us read about or watch these events (often in real time) on small screens on phones in our hands, or sometimes on even smaller screens on our watches. Even those of us who work in technical fields cannot help but be awed at the technological innovation that seems to be exploding around us.

In this dynamic atmosphere, anyone paying attention would find it difficult to believe there is only one technological answer out there for any given technical problem. Instead, when faced with such a problem, we would expect to be able to choose from a plethora of technology solutions—some of which we likely didn't even know existed until we began to fully analyze our problem and start our solution search in earnest. But with this wealth of technological possibilities comes a challenge: How do we quickly and effectively evaluate, compare, and choose the "right" solution from a large pool of varying potential solutions without spending excess time and money on the search?

The DoD is facing this challenge as it works to maintain our technological edge over adversaries who are rapidly catching up. While it is crucial that we continuously explore new technologies (and enhance older ones where feasible) as rapidly as possible, there is not sufficient time, funding, or personnel for the DoD and Services to pursue every technological idea that has promise, raising the questions: Which technologies do we invest in, and how can we get them in the hands of the warfighter as soon as possible? Which capabilities are the most important to satisfy?

Defense leadership views rapid concept exploration and prototyping, the "fail fast/learn fast" mindset, as key to meeting this challenge. In response, the U.S. Navy is implementing an innovative accelerated acquisition methodology to rapidly inform prototyping investments across the Navy and Marine Corps. The tactics and technology exploration and experimentation (TnTE2) method is fostering innovation and is used to quickly respond to high-priority urgent or emerging operational needs. This new methodology brings together operational and technical teams of warfighters and engineers leveraging aspects of a systems engineering methodology called Set-Based Design (SBD) to rapidly assess emerging technologies and engineering innovations against a specific capability-based framework. The methodology expands the tradespace to assess a much larger range of options. The process eliminates options only when they are proven infeasible based on objective quality evidence (OQE), and delays making critical constraining decisions until after the requirements and the solution options are better understood.

Crucial to the success of this method is the ability to quickly and effectively perform complex data analysis on extremely large data sets and then translate the results into formats (including visualizations) that decision-makers can quickly interpret to choose the most feasible solutions to further explore for a specific problem. The information analyzed includes "the ilities," such as adaptability, durability, interoperability, portability, scalability, supportability, and stability, among other non-functional requirements, to assess the operational burden of a specific solution. Decision-makers often have to weigh technical capability against critical parameters such as performance, maturity, cost, schedule, development time, and risk, all of which, when combined and compared, create millions of options in different sets of permutations. Since no commercial or government off-the-shelf tool currently exists that can quickly fuse, analyze, and display all the required data to support the decision-making process, the engineers and data scientists at the Naval Surface Warfare Center Panama City Division (NSWC PCD) developed a new software application tailored for complex data analysis. This new tool lends itself to both the rapid prototyping process and naval system acquisition. The Set-Based Design Evaluation Tool (SET) is a desktop software application that can be run on any computer with a Windows operating system. Currently in its beta phase of development, the SET is evolving through hands-on use by the technical and operational community. Through this user operational system evaluation context, SET is becoming more capable and robust and is already successfully being used to support the rapid prototyping process, including the following:

- Problem definition
- Capability concept generation
- Fleet valuation exercises
- Data analysis from demonstration and experimentation events of individual technologies

SET is designed on the backbone of the SBD engineering methodology, and thus helps ensure a sufficient degree of engineering rigor is applied in the rapid prototyping process—something that is often missing in rapid prototyping efforts. The tool organizes and analyzes the data to help produce and document OQE that is traceable to warfighter missions, scenarios and tasks, and helps define requirements.

This paper describes the history of SET, its current scope of capability (with a recent use case), and what SET will look like in the future as it evolves in capability.

Historical Evolution of SET

In 2014, NSWC PCD's Innovation Cell (iCell) proposed bringing U.S. sea mining into the 21st century by prototyping and demonstrating a modular "smart" mine suite, which would: (1) include communications, command and control, sensors, and both kinetic and non-kinetic effector nodes; (2) launch from unmanned surface and undersea vehicles; and (3) be able to be pre-positioned in international waters to persistently influence the adversary at a time/place of our choosing. The proposed iCell concept gained early DoD and Navy leadership support, and when U.S. Pacific Command (PACOM) released a Joint Emergent Operational Needs Statement (JEONS) in 2015 seeking an asymmetric capability to address the threat of contested environments, PACOM and then-Deputy Assistant Secretary of the Navy for Research, Development, Test, and Evaluation (DASN RDT&E), Dr. John Burrow, felt that the smart mine concept could potentially offer a solution. Burrow tasked NSWC PCD to lead a cross-Naval Research and Development Establishment (NR&DE) Smart Mine Initiative (SMI) to explore innovative concepts and share technologies which could be integrated to meet the vision of a smart mine for the JEONS.

At the time of the release of the JEONS, the DASN was also exploring implementing the innovative SBD systems engineering methodology across the Navy R&D warfare centers to change the paradigm of Navy system design. The SBD methodology, which has been used successfully for years in the automotive industry by Toyota, first emerged for potential use in Navy ship design in 2008 when Vice Admiral Paul Sullivan, then-Commander of the Naval Sea Systems Command, issued a memo that expressed the need for evolving models and analysis tools to be compatible with, among other things, SBD (Singer, Doerry, & Buckley, 2009). An instantiation of the SBD methodology was successfully used by the U.S. Marine Corps in 2013 in concept exploration for an affordable, survivable, high water speed Amphibious Combat Vehicle (ACV) to replace the cancelled

Expeditionary Fighting Vehicle (EFV; Burrow et al., 2014). The first Navy instantiation of the SBD methodology was used in 2014 to develop preliminary designs for the Navy Ship to Shore Connector (SSC; Mebane et al., 2011), a new ship to replace the Landing Craft, Air Cushion (LCAC). The DASN RDT&E thought the SMI effort was a good opportunity to utilize the SBD methodology at the beginning of development of a new Navy capability to be rapidly prototyped to meet an urgent warfighter need. In 2016, NSWC PCD and its cross-warfare center SMI team began to incorporate aspects of SBD methodologies into a six-month analysis of the smart mine capability tradespace. The goal was to identify feasible configurations for potential prototyping.

In simple terms, SBD is a methodology that allows designers to fully explore a design tradespace, evaluating very large numbers of design configurations early in the design process to quickly eliminate designs which are not feasible based on OQE so that the most promising ideas can be modeled or prototyped to determine viability prior to choosing a final design. In its most basic form, SBD is design discovery by way of elimination. The delay in final design choice until superior OQE data is gathered results in better understanding of the requirements, more optimal designs, lower risk, lower cost, and increased stakeholder interaction. Using this design methodology, engineers are not selecting the best solution so much as they are eliminating the worst. It allows for convergence on a solution set that increases understanding of design decision impacts.

SBD is a significant paradigm shift from the Navy's traditional design methodology, which follows a classic design path: (1) Converge as quickly as possible on a solution (a single "point" in the identified solution space) that has acceptable risk and fits within the limitations of either budget or available time, or both; then (2) rapidly and incrementally develop and evolve that solution until it meets the requirements and can be fielded to the warfighter. This can be an effective approach if the optimal solution is selected at the start (highly unlikely). Choosing that optimal solution is challenging, however, especially when the requirements are relatively immature and not well understood (a common acquisition problem), or when the design incorporates technologies that don't perform as expected (another common acquisition problem). What happens when the solution selected proves to be less than optimal and issues arise? The process, which planned and funded solely for success, remains locked on that "point-based design" and the program manager has to spend extra time, effort, and funding to modify the design until it meets the (potentially immature, and more likely ill-conceived) requirements.

SBD takes a very different approach. As noted previously, instead of quickly converging on a single point based design solution, SBD expands the tradespace to assess a much larger range of options that includes cross domain intersections. It delays making critical decisions until later in the process when both the range of requirements and the potential solution options are better understood through OQE, data analysis, modeling and simulation (M&S), and rapid prototyping.

A good analogy for the value of SBD can be found in the story of those infamous builders "The Three Little Pigs," who classically used a point-based design approach to design a shelter to protect themselves from the Big Bad Wolf. Under their point-based design approach, they generated hard and fast requirements too early with incomplete knowledge of the problem, resulting in incorrect assumptions, such as the structure had to provide shelter, it had to stand up to strong wind, and it had to hold at least one pig. When they began looking for solutions to meet their requirements, they constrained their trade space to the design options they were familiar with rather than expanding the space to look for more innovative options. For example, the type of shelter they quickly settled on was a building (expanded trade space options may have included a tree house or a cave or an underground home or a wolf-free island that needed no shelter). They chose materials they were most familiar with, such as straw, sticks, and bricks. An expanded tradespace may have included glass and metal. They then proceeded down three independent paths and conducted their trade studies in stovepipes. Their studies for materials, floor plan, roof pitch, and so forth, were all conducted independently with no cross-domain intersection considerations. No one understood the core required capability (the critical design factor), which was not maintaining security of the pigs as much as wind resistance. As a result, the first design, the straw house (chosen because it met the basic requirements and appeared to be cost effective), failed integration and operational testing when the wolf came knocking. They then had to redesign the straw house for a better (but not fully) understood requirement for wind. Under their point-based design approach, it took multiple iterations—each with an associated cost and schedule—before they gained enough knowledge to inform the final design and realize a brick house would work. Their point designs became hindsight engineering. And with a dangerous enemy like the wolf, they could ill afford these high-risk return trips to the materials pile to get it right.

Under the SBD approach, the pigs would have designed all three houses concurrently, and then used field and lab testing, low-efficacy models, and simulation techniques to eliminate poor design configurations prior to committing resources for building the final house. They would have made design decisions based on OQE, and they would have had a better understanding of how to meet the now fully understood requirements. Bottom line: If they had used the SBD approach, they could have saved time and money and all lived out their lives safely and comfortably in brick homes (or maybe even in a cool cave or on a wolf-free tropical island).

When the wolf is at the door, SBD can show that not all feasible designs (those that look good on paper) are viable (actually work), which allows leadership an opportunity to make important decisions and understand their impact before the house is built. The SBD engineering effort has a cost and schedule that is front loaded. It may not be quicker getting started; however, the savings in cost and schedule come in the latter half of development by avoiding costly and lengthy redesign, test, and production reiteration.

Specifically, the SBD methodology does the following:

- Considers large data “sets” of candidate solution alternatives in the trade space (often containing millions of potential configurations)
- Takes advantage of modern automated analytical frameworks that leverage high-speed computing power to develop, explore, manage, and visualize large data sets
- Reduces the trade space in a progressive, deliberate manner by eliminating alternatives only when objective evidence (analysis, M&S, rapid prototyping) shows they do not meet the necessary criteria (i.e., feasibility/viability and cost/schedule/performance)
- Increases knowledge as the sets of alternatives are narrowed
- Converges to more globally optimal solutions with greater fidelity
- Reinforces confidence in final recommendations to leadership with a pattern of reproducible, defensible artifacts in support of the decision process, specifically before highly constraining decisions
- Builds a body of lessons learned on options that were eliminated, which can inform future efforts

A critical requirement of SBD implementation in system development is a means to rapidly conduct the complex data analysis and translate the results for decision-makers. For the previous Navy SBD efforts, a one-of-a-kind automated analytical framework tool called the Framework for Assessing Cost and Technology (FACT) was developed for each specific effort to provide visual simulations that integrated data and model input on design, cost, schedule, etc., to allow leadership to quickly see how the various design choices affected outcome.

Specifically, the FACT tool (whose capabilities are shown in Figure 1) enabled the efforts to

- Process large data sets through integrated M&S
- Provide data integration, processing, and concise visuals of data relationships and solution alternatives
- Allow users to understand and rapidly assess interdependencies between requirements, components, and variables of large and complex data sets
- Allow decision-makers to explore the tradespace and compare alternatives
- Allow leaders to maintain and manage an evolving requirements set

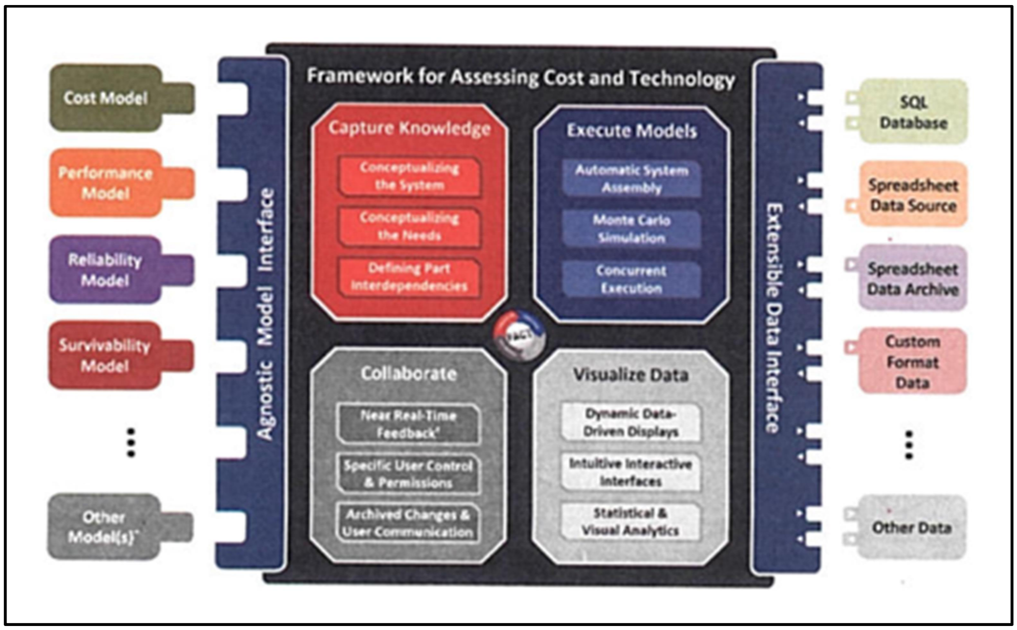

Figure 1. Framework for Assessing Cost and Technology (FACT) Structure

While the FACT tools developed and used for both previous efforts shared a common software architecture, each version required unique software coding, man-hours, and expense to tailor it to the subject matter. Since SMI did not have the time nor funding available to pursue a lengthy rework of the existing tool, when the SMI effort launched NSWC PCD and the Georgia Tech Research Institute (GTRI) (which developed the FACT software for the U.S. Marine Corps) worked together following the FACT example to create a less detailed, but more adaptable, version of the previous tools to meet the needs of the smart mining effort. Creating the SMI version of FACT took six months of focused development and coding. In the end it was a single instantiation of an SBD tool that was developed for a single purpose. It built upon and progressed previous SBD tools, as it did allow the user to quickly (~30 minutes) analyze very large data sets. At the end of its development, the SMI FACT was able to help leadership visualize and analyze a tradespace of 1.9 quadrillion possibilities that resulted in a recommendation of nine feasible configurations that included cost, schedule, risk, and performance.

Since the DASN planned to implement SBD across the entire Navy R&D community, it became clear that a new FACT-like tool was needed that was flexible and robust enough for systems engineers to apply to any SBD system development effort without the need for major recoding. After the SMI six-month effort was completed, NSWC PCD systems and software engineers began developing SET to fill that tool gap. The SET team is building on the FACT capabilities, which improved with each of the FACT instantiations (as shown in Figure 2). The SET team has been working on the tool continuously since 2016, adding more capabilities daily (sometimes “on the fly” as needs emerge while being used to support an R&D event). As noted previously, the tool is still in beta form, but it is being used to support current rapid acquisition efforts using SBD methods. The vision for SET is to reach the robustness of the previous FACT tools (including being able to ingest inputs from external models such as cost models) in an “off-the-shelf” version flexible and powerful enough to work across all problem solution efforts employing a SBD methodology.

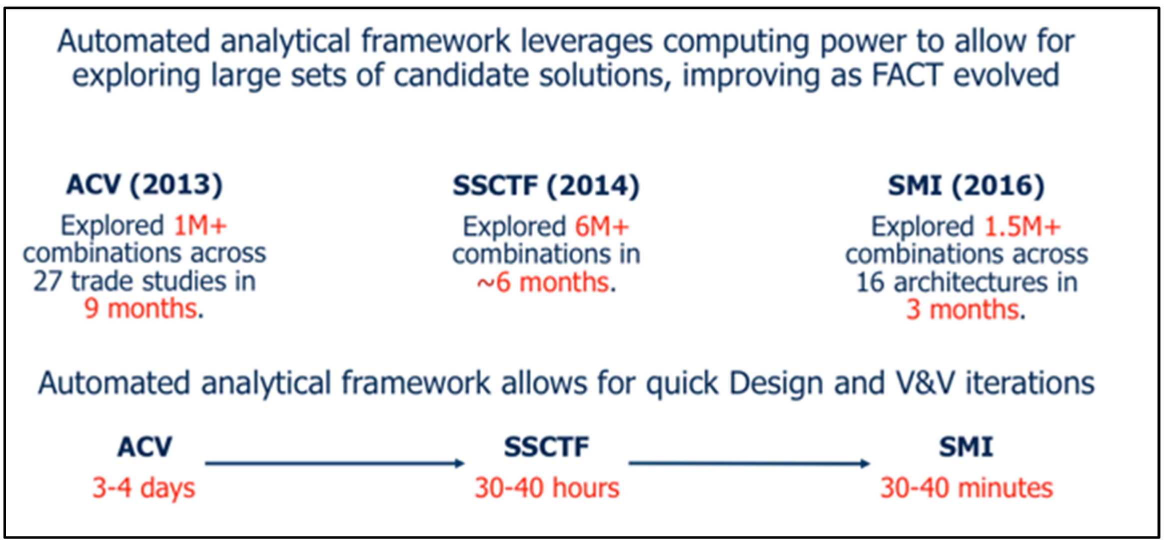

Figure 2. Improvements in FACT Performance

Current SET Capability and a Representative Case Study

SET provides an easy-to-use tool to quickly process extremely large data sets (into the trillions), integrate and process/filter the data, and provide concise visuals (such as scatter plots and histograms) of data relationships and solution alternatives. Currently it is limited to evaluation and comparison of individual technologies, but the envisioned end state will allow for evaluation and comparison of sets of configurations which can be quickly formed and re-formed using the tool to allow decision-makers to clearly see how different design choices in configurations affect system outcome.

SET is structured around the elements of a Force (e. g., the warfighter) Engagement Process framework using tailored SBD elements that can be used to support the rapid prototyping process and overall Navy system development. The framework translates a specific, emerging Fleet or Joint Force concept of operation (CONOP) into increments of capabilities. Those increments of capability, presented through a SET visualization tool that models a Capability Concept Wheel (CCW), are used during a series of scenario-based wargames with teams of warfighters to provide insight into the relative value of increments of capability to effective mission operation(s). Once the capability concepts which are the most highly valued by the warfighters are identified, a robust database of relevant technologies that can support those capability concepts is developed through data calls and calls for proposals. Subject matter experts (SMEs) then analyze and bin the submitted technologies by capability concept, and assess them operationally and technically. Technologies are eliminated from consideration only when OQE shows them to be infeasible for helping solve the problem. The resulting narrowed group of technologies are then assessed operationally (in a scenario) and technically by warfighters in an Advanced Naval Technology Exercise (ANTX). In cases where a technology is supported by such a high degree of OQE that further evaluation is superfluous, the technology may skip an ANTX and begin planning for prototyping.

The Force Engagement Process framework (shown in Figure 3) underlying SET involves three phases:

- Force Valuation
- Assessment Workshop
- Demonstration and Assessment

A fourth phase is envisioned for the future. It includes the integration of models (e. g., cost and/or performance), so that decisions on acquisition, contracting, and system prototype configurations can be completed. Data analyzed through SET will lead to recommendations for continued system design of feasible configurations that lead to execution of viable designs and solutions.

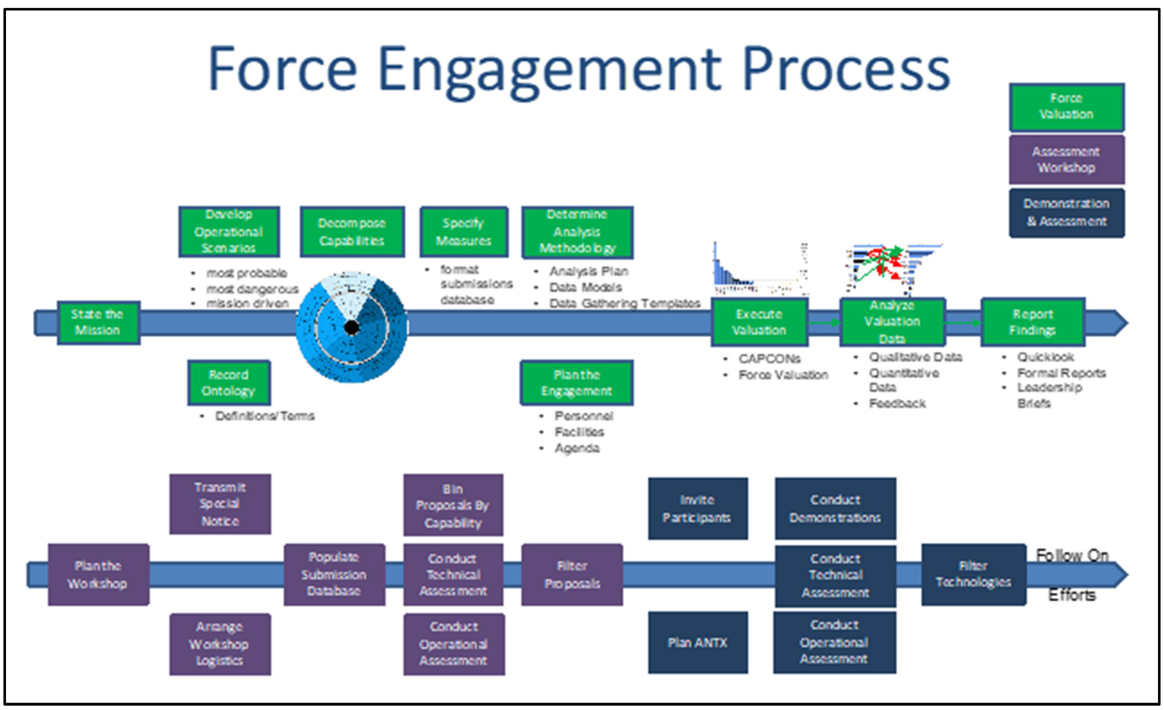

Figure 3. Force Engagement Process Underlying SET

In the Force Valuation phase, the systems engineering team makes the engineering preparations for and executes a Force Engagement Team (FET) valuation exercise in which warfighter teams with a mix of mission-appropriate skill sets use a Capability Concept Wheel in a tabletop wargame to determine which of the capability concepts they value most highly in a relevant operational scenario. In this phase, SET can be used to record the definitions of terms so all participants use the same taxonomy; automatically create the Capability Concept Wheel based on manual inputs from the capabilities decomposition; record the points assigned during the valuation wargame; analyze the valuation results; and generate reports (including visualizations such as scatter plots and histograms).

In the Assessment Workshop phase, the team issues data calls and requests for proposals to collect data on relevant technologies that potentially support the most highly valued capabilities. The collected data is then used to create a technology database. SMEs meet to bin the technologies by capability, then conduct technical and operational assessments to eliminate technologies based on initial filtering criteria, thus narrowing the number of potential technologies going into the ANTX. In this phase, SET can be used to import the technology database, bin the technologies, record the assessment data, and filter the technologies.

In the Demonstration and Assessment phase, the team plans and executes an ANTX or other demonstration in which technologists are invited to bring and demonstrate the filtered technologies so warfighters can physically view them and conduct technical and operational assessments. In this phase, SET can be used to create the electronic assessment forms, record the results (through individual networked computer tablets) from the technical and operational assessments, filter the technologies based on assessment results, and generate reports (including visualizations).

The current beta version of SET was most recently used to support a recent Urban 5th Generation Marine (U5G) effort. As outlined in the Marine Corps Operating Concept (MOC) and the Marine Corps Intelligence Activity's Future Operating Environment, the growth of crowded, poorly governed, or lawless areas (particularly in and around the world's littorals) will force future commanders to consider how to conduct operations in complex terrain. In 2017, a U5G Task Force was established to develop concepts that enable situational awareness, counter reconnaissance, maneuver, fires, and command, control, communications, computers and information (C4I) operations within and among the populations that reside in the urban littorals. The task force—comprising a core team of operational, acquisition, and technical subject matter experts from Headquarters Marine Corps Combat Development and Integration (CD&I), Marine Corps Warfighting Lab (MCWL), Marine Corps Systems Command (MCSC), and the NR&DE—is charged with executing a progressive series of ANTX that will inform emerging concepts of operations and future acquisitions.

The first end-to-end exercise of the TnTE2 method, U5G ANTX 2018, was held in March 2018 at Marine Corps Base Camp Pendleton, CA. The ANTX was structured to provide warfighters with the opportunity to assess the operational utility of emerging technologies and engineering innovations that enhance the U5G concept of operations as it applies to a Marine Air Ground Task Force (MAGTF), which is given missions to operate in an urban environment.

The ANTX explored the five domains of air, space, cyber, logistics, and intelligence, with the focus on how those areas affect the operation in the urban environment at the company level. The ANTX used two vignettes to provide context for employment: (1) A rifle company must secure a key piece of infrastructure in a hostile environment where adversaries blend with civilians requiring a high degree of urban situational awareness, precision effects, and minimal signature; and (2) A rifle company, as part of a larger operation, must conduct offensive operations to clear a complex urban area consisting of multiple city blocks, underground corridors (subway, sewer basements, etc.), and multi-story buildings. Once cleared, they must secure and defend the area while potentially providing assistance to any remaining civilians. During the course of both vignettes, the rifle company is continually conducting offense, defense, and stability.

SET was used to support each of the three phases of the Force Engagement Process in the U5G effort.

Primary goals for SET during the ANTX event included the following:

- Improving methods, processes, and tools
- Integrating assessments of operations, technology, and capability
- Leveraging technology to enhance data capture and analysis
- Providing traceability to U5G core capabilities
- Providing data longevity for future study
- Providing insight upon which solutions are ready for rapid acquisition, experimentation, or are a science/technology of interest

Prior to the start of the ANTX, Operational and Technical SMEs helped draft the criteria, scales, and weights associated with assessing the candidate technologies. The ANTX event was split into two days of Limited Technical Assessments (LTAs) and 2 days of Limited Objective Experimentation (LOE). During the LTAs, squads of Marines handled individual pieces of technology at static displays or as part of live demonstrations. During the LOEs, platoons carried out operational missions, both day and night. Three platoons were issued multiple pieces of technology while rotating between mission objectives and operational locations. Upon conclusion of each LTA or LOE event, an embedded data collector would capture both quantitative and qualitative assessment data from individual marines, and the technical assessors via the SET assessment interface. Technical assessments were captured by tailored, diverse groups vice individuals to ensure subject matter expertise was factored in and the groups could build upon separate areas of knowledge for a complete assessment: mechanical, electrical, computer science, and so forth. Over four days, SET processed 2,664 total assessments: 2,210 operational, 304 technical, and 150 scenario based.

SET provided near real time statistical observations on operational and technical performance of demonstrated technologies from the warfighter and engineering perspectives in the form of histograms and scatter plots. It translated concepts of capability assessment, technical assessment, and operational assessment into data views which enabled cross referencing of performance not only from a total score perspective, but it enabled drilling down to specific questions of interest, such as operational relevance or personnel burden. SET also highlighted those technologies that traced back to the top capabilities required for success within the proposed scenarios.

Future developments of SET may be able to provide justification criteria for DoD acquisition by providing the linkage between capability requirements and in field testing.

The next several figures are good representations of data from the U5G ANTX. Figure 4 presents the Capability Concept Wheel that the U5G team created using SET for the Force Valuation phase. Figure 5 presents a visualization of the Assessment Workshop phase binning of the 93 technologies that were evaluated. Figure 6 presents an example (non-U5G) of an assessment form created using SET (similar to what was created for the U5G ANTX). Figure 7 provides a sample of a visualization from the U5G ANTX assessment results.

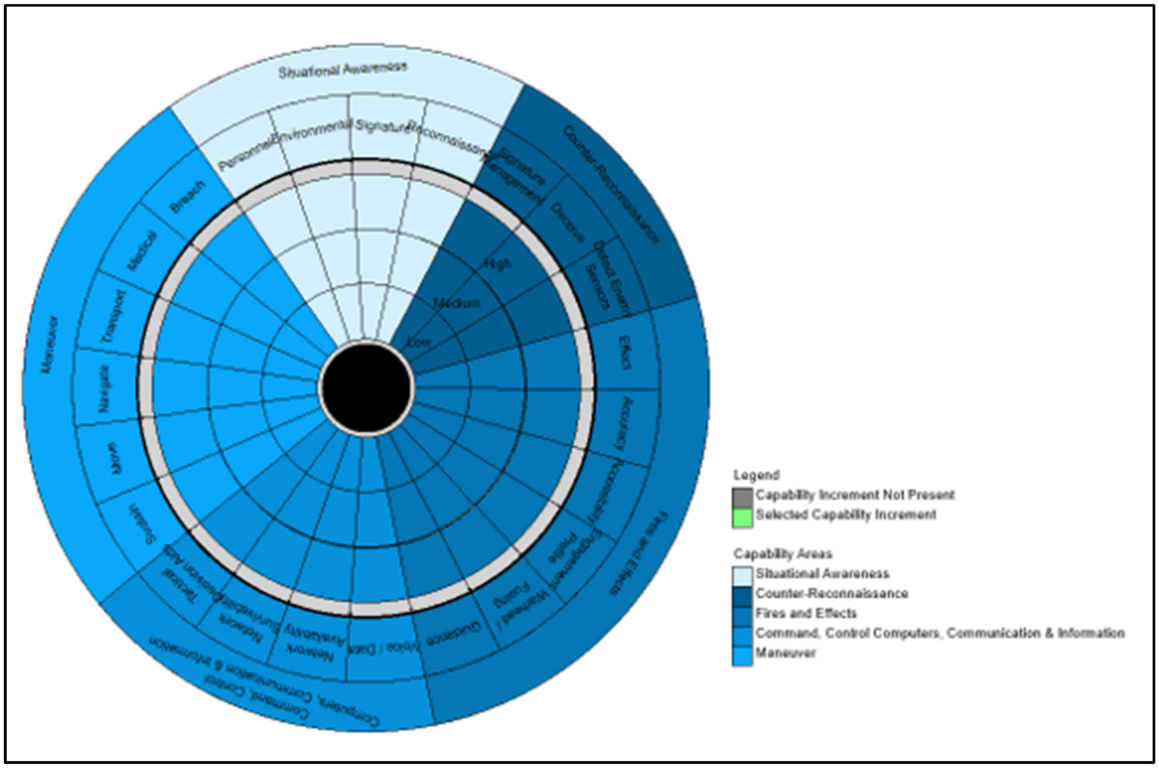

Figure 4. U5G ANTX 2018 Capability Concept Wheel

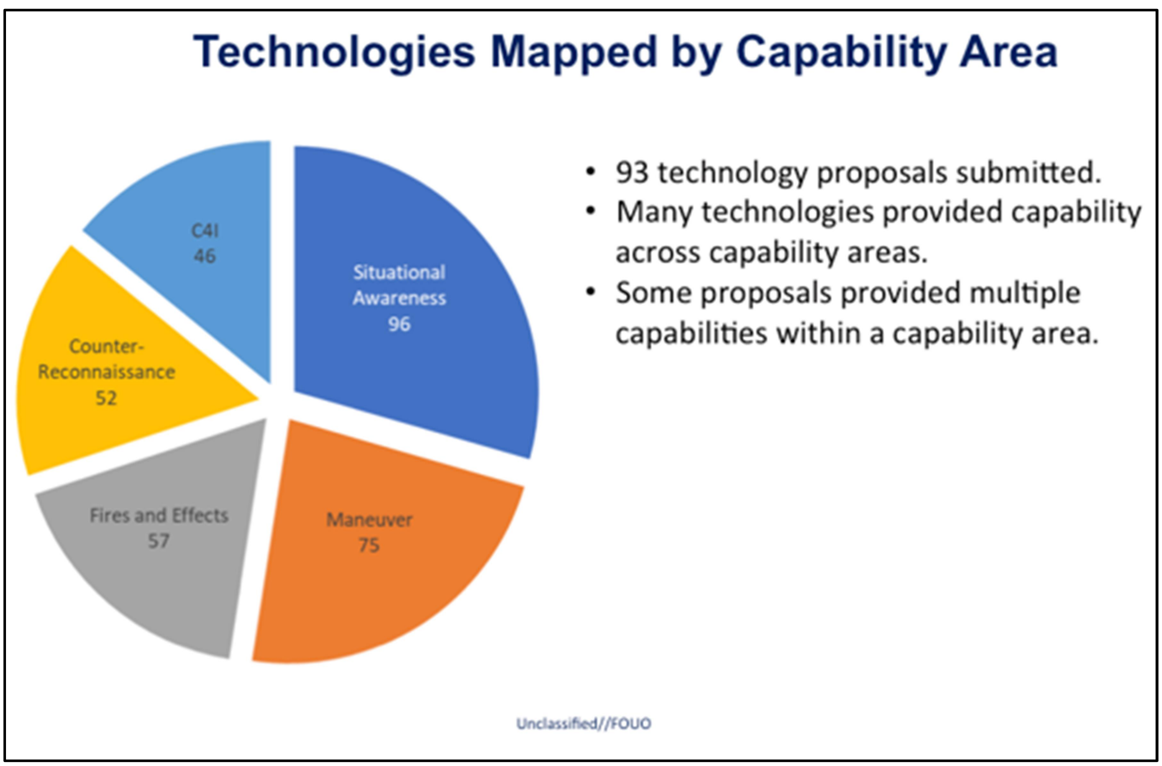

Figure 5. U5G ANTX 2018 Technologies Mapped by Capability Area in SET

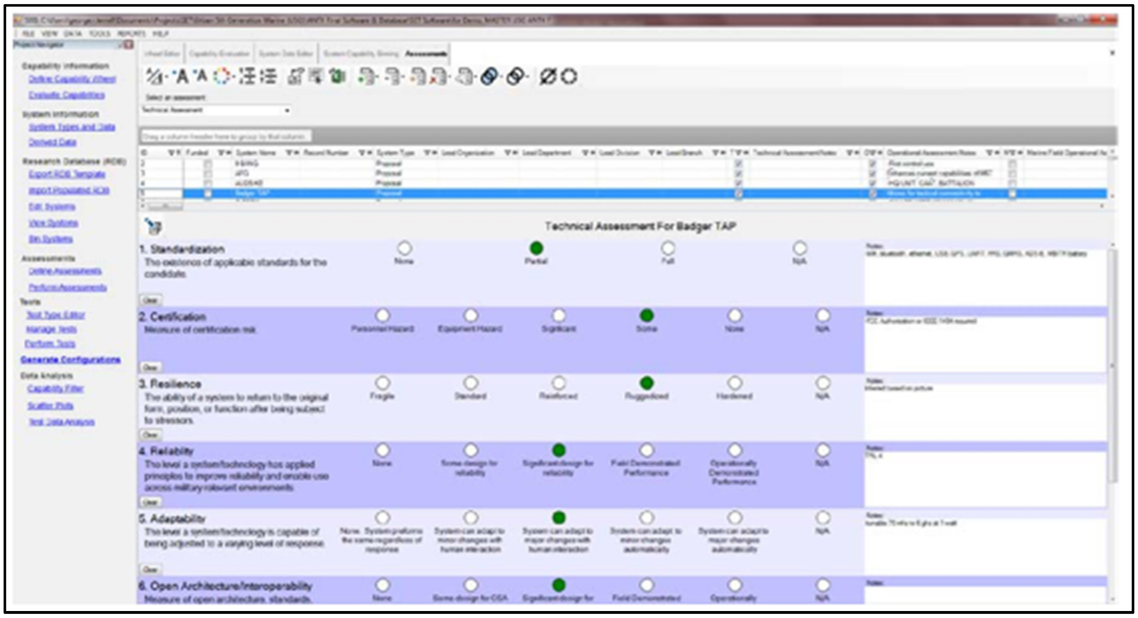

Figure 6. Sample Assessment Form Created With SET

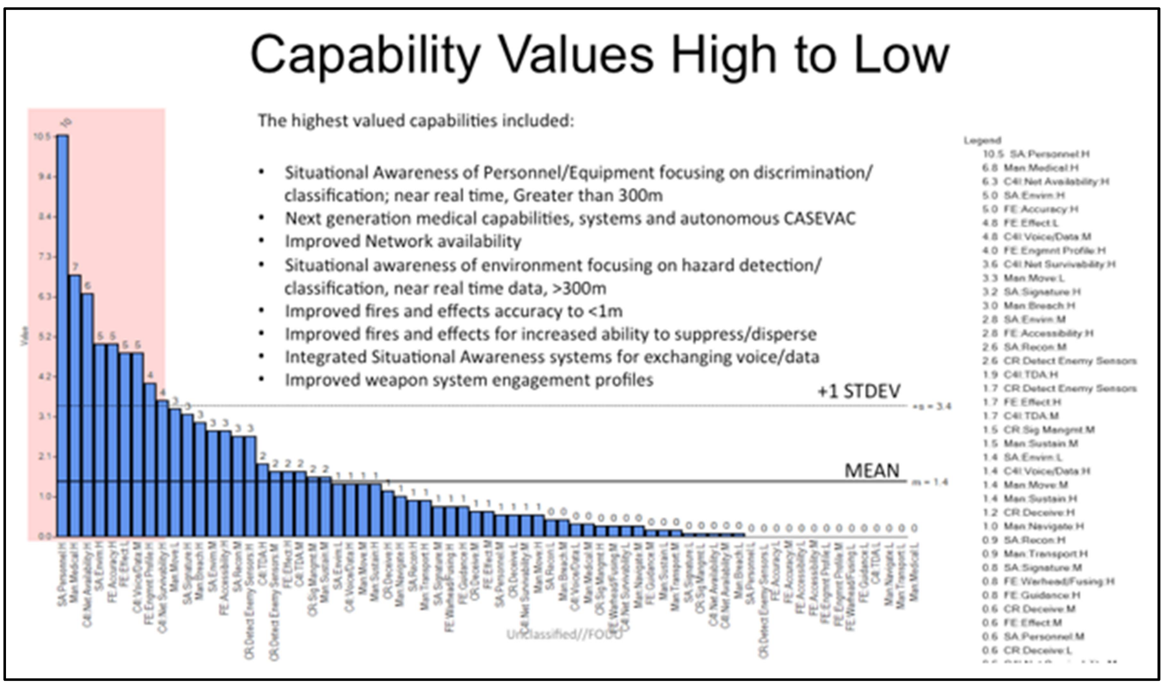

Figure 7. Example of Assessment Results Visualization From SET for U5G ANTX 2018

Next Stages of SET Development

In its current instantiation, SET successfully evaluates measures of stakeholder utility and may apply these measures against technology solutions whether they are tactics, process, or systems. However, to come to full realization as an automated analytical framework tool, current development needs to address not just stakeholder utility, but also a means to understand the relationships between sets of solutions and how they may drive the feasibility of design.

A close focus on improving the user interface will help fortify the methodology and help teams adopt the principles of SBD. Focus on SET outputs will aid in institutional learning, reuse, and knowledge retention. New designs will be able to build upon previous explorations.

Functions that are currently under development in SET include the following:

- The capability to create design sets and configurations, providing definition and constraints
- Establishing mathematical relationships to set intersections
- Providing a GUI which allows input, modification, and visualization of design-impacting attributes
- The capability to evaluate a design space for feasibility and dominance, specified by a set of constraints and given specific functional relationships
- The capability to interface with other models, such as cost and risk, to provide other interpretations of set feasibility

Ultimately, the goal of SET is to help inform future design and improve design quality by allowing greater design space exploration and providing support to a methodology which may provide solutions more resilient to requirement changes, grant early understanding of design relationships, and reduce design rework.

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